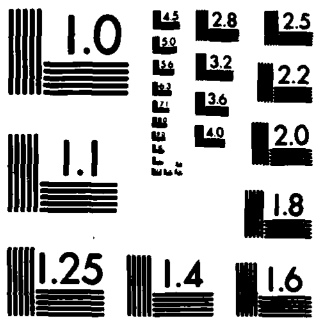

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of Water Pipes

Kevin L. Carey

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COLD REGIONS TECHNICAL DIGEST No. 82-1, MAY 1982

USA Cold Regions Research and Engineering Laboratory
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The freezing and blocking of water pipes

Kevin L. Carey

Introduction

One of the biggest concerns in designing utilities for cold regions is how to keep water pipes from freezing. Frozen pipes and mains cut off the water supply, causing time and money to be spent in restoring service. Furthermore, the efforts to restore service are often made in an atmosphere of urgency, under difficult working conditions. Thus, rather than designing systems that can withstand the effects of freezing, utilities engineers seek systems that won't freeze in the first place.

While it is feasible to design water systems that won't freeze under normal winter conditions, it is harder to design for extreme weather. Severe conditions are more difficult to define, for one thing. Consequently, designers occasionally include provisions for electrical resistance thawing of frozen pipes and for replacement of damaged sections of pipe, although they hope that these techniques will rarely have to be used.

The topic addressed in this article is the freezing and blockage of water pipes that are full, with the water either flowing or still.

The author, a civil engineer, is a member of CRREL's Construction Engineering Research Branch.

It has long been assumed that when the water in a pipe freezes the ice begins to form on the inside surface of the pipe and grows uniformly inward (annular growth), until finally the pipe is completely blocked. Under this hypothesis, the freezing process is fairly slow and quite predictable. The only difference between the freezing of flowing water and static water is a difference in freezing rate due to the addition of heat via the water flow.

Recent studies of pipe freezing, however, have shown that the freezing process is much more complicated than this. Furthermore, the process differs substantially for still water and flowing water. Water flow can become blocked much quicker than was supposed under the earlier hypothesis, and the actual freezing process appears to be less predictable in terms of time and heat loss. These recently observed phenomena are the primary focus of this article. For more extensive reviews of the annular growth of ice, see the papers by Zerkle and Sunderland (1968), Ozisik and Mulligan (1969), and Stephan (1969) listed on page 11.

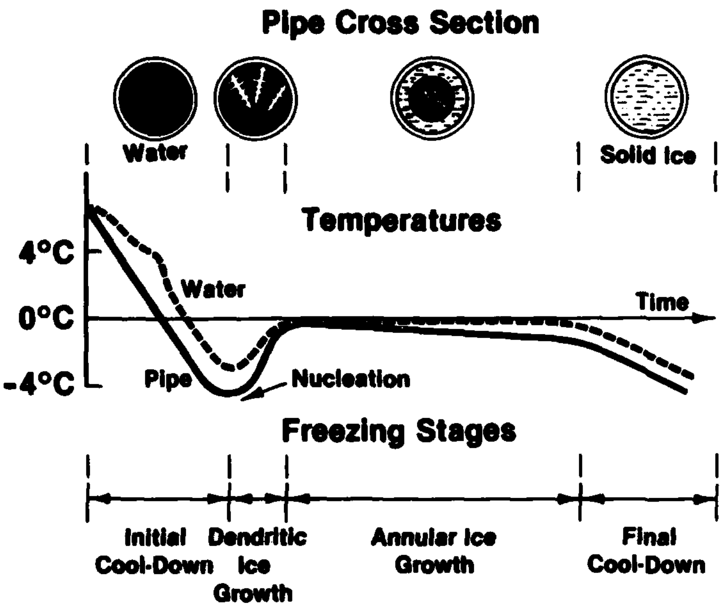
The results of recent experimental work are described below.

Freezing of static water

R. Gilpin (1977a,b,c, 1978) has studied the process of freezing of static water in pipes. He recorded the temperature of the pipe wall and the water, measured heat losses, and watched ice form inside transparent pipe sections. He made two important findings. First, the water is supercooled significantly before ice nucleation begins, typically reaching -4° to -6°C. Second, because of the supercooling, ice formation begins with the development of dendritic ice—"thin 'feathery' crystals which are interspersed with water."

The dendritic crystals grow rapidly, in as little as half a minute, and release heat of fusion. This quickly raises the temperature in the pipe to 0°C and brings the dendritic growth phase to an end. Then the expected annular growth of solid ice begins, and the dendrites become more solid while they are slowly being incorporated into the growing annulus. Eventually the solid annulus occupies the entire cross section of the pipe. The pipe and its frozen contents then cool further to approach the ambient temperature.

For all practical purposes the pipe becomes blocked when the dendritic ice first appears. Gilpin measured the water pressure gradient required to start flow (in other words to

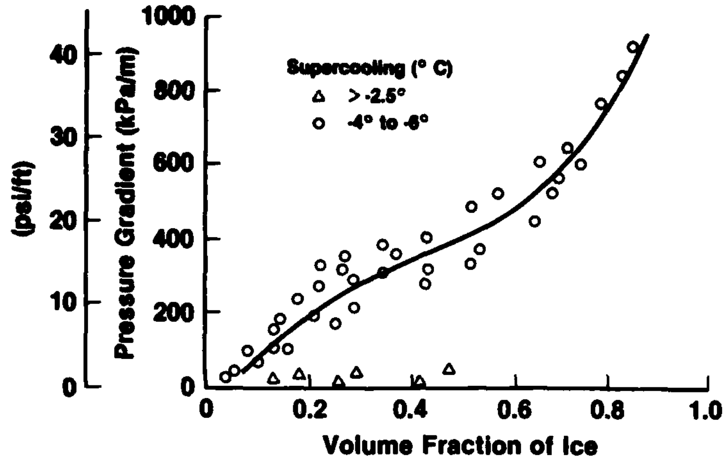


1. Freezing history of still water in a pipe (Gilpin 1977c).

break through the dendritic ice) as a function of the volume of ice within the pipe. He found that in a ½-in. (12.7-mm) ID copper pipe, with a spontaneous ice nucleation temperature in the range of -4° to -6°C, when only 7 to 8% of the pipe volume was frozen, a pressure gradient of 2 psi/ft (45.24 kPa/m) was required to start the flow. When freezing was allowed to proceed until greater volumes were frozen, higher pressure gradients were required. When 80% of the volume was frozen, for example, the pressure gradient required to rupture the dendrites and start the water moving was 36 psi/ft (814 kPa/m). These findings are illustrated in Figure 2.

The amount of supercooling that occurs before nucleation is important. The greater it is, the more the pipe is blocked by dendritic ice for a given amount of heat loss. Gilpin demonstrated this by inducing nucleation after supercooling by striking the pipe when the temperature of the water within it was -2.5°C or above. Nucleation was evidenced by a rapid rise to 0°C caused by release of the heat of fusion. At any measured heat loss following nucleation, up to a loss sufficient to freeze half the contents of the pipe, the pressure gradient required to initiate flow was negligible. This is also shown in Figure 2.

Evidently the difference in the pressure gradient required



2. Pressure required to initiate flow in partially frozen 12.7-mm-ID copper pipe containing static water (Gilpin 1977c).

to start flow is due to differences in the integrity of the ice formed within the pipe. More supercooling produces more dendritic ice, which strengthens significantly with continued heat loss. Less supercooling produces fewer dendrites, and further heat loss after nucleation appears to promote the growth of annular ice at the expense of strengthening the dendritic ice, leading to lesser start-up pressure gradient requirements.

The first conclusion drawn from the above is that a pipe is in danger of blockage when the water has cooled to -3 °C or lower, and this blockage may occur in far less time than it takes for a solid ice annulus to grow to the center.

The next conclusion drawn, in the interest of preventing ice formation or minimizing the difficulty of restoring flow if freezing does occur, is that supercooling of the water within the pipe should be prevented or held to a minimum. Expressed another way, if nucleation is inevitable, then it should be encouraged to happen at the highest possible temperature. While nucleation will occur spontaneously at -4° to -6 °C, a physical disturbance may induce it at a higher temperature. In many piping installations this physical disturbance can be provided by low-velocity circulation. The small quantities of "slush" so produced can be carried in the flow without causing blockage, if there are no severe constrictions in the piping system.

Studies by McFadden (1977) have suggested that the rupturing of pipes may be due primarily to nonuniform heat loss along the length of the pipe. In the preceding discussion of

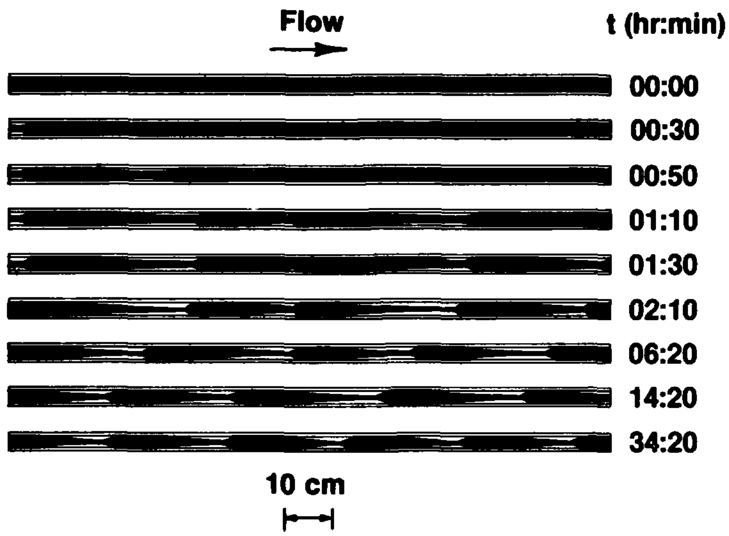
Gilpin's work, the underlying assumption was that the heat transfer and phase change conditions that exist in one section of pipe are present in all sections. But practically speaking this is not the case. Fittings, valves, and variations in the materials surrounding a pipe all lead to variations in heat transfer along it. Thus it is likely that complete freezing and blockage occur at some locations while at others the water remains partly or completely unfrozen. Continued freezing in the less-frozen sections exerts high pressures on the unfrozen water. The pipe then ruptures in these sections that are the last to freeze. To control the locations of the regions that are last to freeze, and to prevent pipe rupturing and damage, McFadden proposed insulating selected pipe sections and equipping them with cheap pressure-relief devices. In this way, potentially damaging internal pressures could be directed to specific locations and harmlessly vented. Pipe thawing would still be necessary, but repair would be eliminated, and only the pressure-relief devices would have to be serviced.

Freezing of flowing water

We again turn to Gilpin, whose recent work (1979, 1981) has focused on the formation of ice in pipes containing flowing water. His experimental apparatus consisted of pairs of concentric glass pipes, with the inner pipe carrying water and the annular space carrying coolant, all within an acrylic plastic box filled with an ethylene glycol and water mixture. This set-up permitted ice formation in the inner pipe to be observed and photographed. A little dye was added to the water to enhance contrast. Temperatures, water flow rates, heat flow rates, etc. were monitored.

The conventional view holds that freezing of water flowing through a pipe begins with the formation of annular ice on the interior pipe wall and that this annular ice progressively thickens downstream, producing a tapered flow cross section. In this view, blockage occurs at the spot where the passage finally tapers to zero diameter. The annular ice may thicken not only spatially, but also temporally if the incoming water temperature drops, or if the heat flow away from the pipe increases.

According to Gilpin's work, this conventional view is a fair representation of the process in its earlier stages. But it is a *transient condition, with the final* steady-state condition being quite different. Gilpin finds that instability at the ice/water interface, associated with abrupt changes in turbulence and



3. Time-sequence of ice structure formation in a pipe with turbulent flow (Gilpin 1981).

hence heat transfer rate, ultimately produces a rippled ice surface as shown in Figure 3. In general, the flow cross section gradually tapers and then abruptly enlarges, then tapers and enlarges again, and so on.

During the transient period the "ice bands," as Gilpin calls them, migrated slowly upstream until they reached an equilibrium in terms of position and spacing. Differences were observed in the way the ice bands first appeared and migrated, depending on whether the initial flow was laminar or turbulent. But the final steady-state form of the ice was essentially the same throughout Gilpin's study.

To more fully describe this ice formation in terms that are relevant to pipe friction and ice blockage, we must first define the following terms:

d = minimum diameter of flow passage at an ice band

D = inside diameter of pipe

f = friction factor

Re_D = Reynolds number defined with D as the effective length = $V_0 D/\nu$

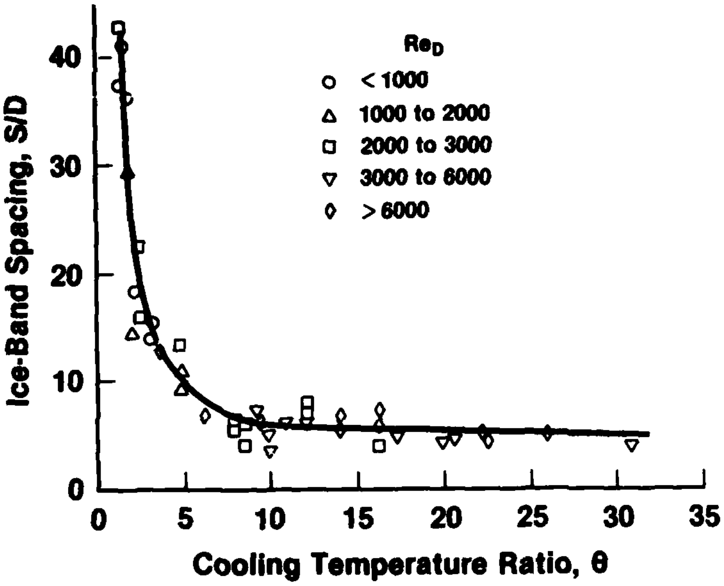
S = spacing between ice bands

T_c = temperature of coolant in Gilpin's apparatus

T_f = freezing point of water

T_w = temperature of water

V_0 = water velocity in the unobstructed pipe



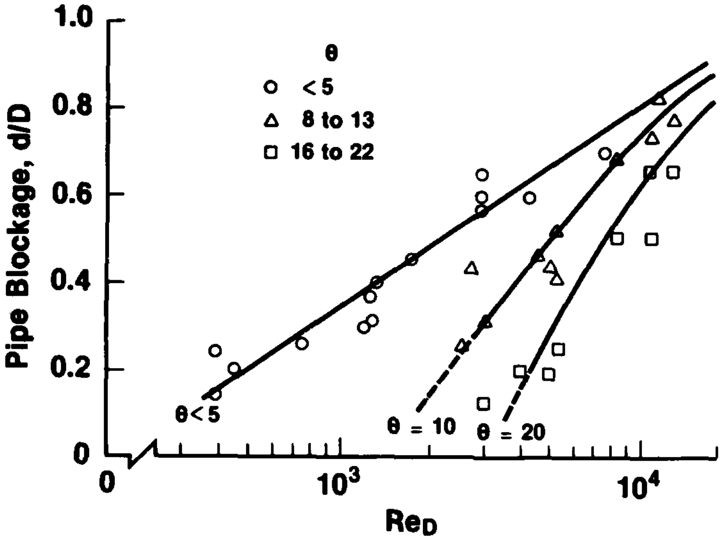
4. Normalized ice-band spacing in a pipe with steady-state ice formation (Gilpin 1981).

θ = cooling temperature ratio = $(T_f - T_c)/(T_w - T_f)$

ν = kinematic viscosity of water.

The two variables that influence the behavior of the ice in the pipe are the Reynolds number Re_D and the cooling temperature ratio θ. (The Reynolds number characterizes the flow as laminar, transitional, or turbulent.) The normalized wavelength of the ice bands S/D has a strong dependence on θ when θ is small. This is seen in Figure 4, where the greatest wavelengths are associated with the smallest values of θ, i.e. the most gradual cooling. For values of θ greater than about 10, however, the ice band wavelengths are about constant at six times the pipe diameter. This dependence of S/D on θ is independent of Re_D, although Gilpin points out that there can only be a limited range of Reynolds numbers for any given value of θ with ice being present in the pipe but not freezing to the point of blockage.

Of great interest with respect to potential pipe blockage is the neck diameter—the diameter of the flow cross section at the narrowest points. The neck diameter d/D is plotted against Re_D in Figure 5. The most interesting finding is that d/D appears to depend only on Re_D, and to be independent of θ when θ is less than about 5. In other words, lowering the pipe temperature, that is, increasing θ, does not lead to thick-



5. Normalized minimum cross-section diameter (neck diameter) in a pipe with steady-state ice formation (Gilpin 1981).

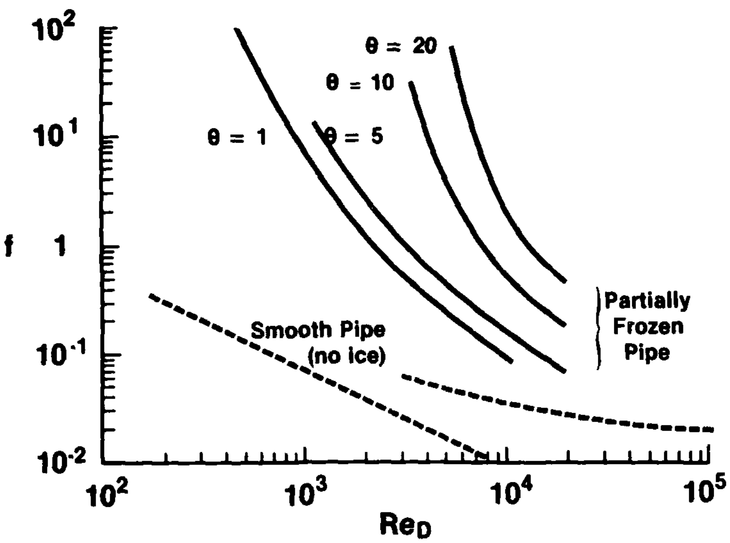
ening of the ice as might be expected, but rather to a progressively closer spacing of the ice bands. However, if θ is greater than 5, d/D depends on both θ and Re_D. For increasing θ, with Re_D held constant, d/D decreases (the minimum cross section decreases) and blockage is more likely. For constant θ, Re_D must *decrease* for d/D to decrease.

The friction factor f, of course, is affected greatly by the ice formation. Actually, the head loss or pressure drop in the partially frozen pipe is made up of "wall" drag, as in any pipe, plus the "nozzle" losses that occur at each ice band. Thus the head loss occurs in somewhat of a step-wise fashion. But for pipes that are long relative to the ice-band spacing S, the relationship for the effective f due to "nozzle" losses may be given by:

$$f = \frac{\Delta P}{\frac{1}{2}\varrho V_0^2(L/D)} = \frac{1}{(S/D)}\ \frac{1-\delta^4}{\delta^4}$$

where ΔP = pressure drop in the pipe section
ϱ = mass density of water
L = length of the pipe section
δ = diameter ratio = d/D
and the other terms are as defined before.

Using the relationships shown in Figures 4 and 5, Gilpin produced Figure 6, which, for partially frozen pipes, shows



6. Friction factor in a pipe with steady-state ice formation (Gilpin 1981).

the relationships between Re_D and f that are implicit in the above equation for various values of θ. Hydraulics people will recognize Figure 6 as the familiar Moody Diagram. Not surprisingly, the friction factor rises dramatically as Re_D decreases with θ fixed, or as θ increases for a constant value of Re_D.

Figure 6 should not be interpreted as a general case, but as indicating typical behavior. Actual curves will depend upon the type of thermal boundary condition (uniform wall flux or temperature) and may vary considerably if the pipe is of significantly different diameter than that used in the study (33 mm).

Finally, pipe blockage or freeze-up while water is flowing can only be qualitatively discussed. While Gilpin describes specific freeze-up results for his particular experimental apparatus, he points out that freeze-up is really a system problem, and cannot be described in a totally general way. This is because freeze-up is not simply a function of the ice growth process, but is also dependent on the pressure-discharge characteristics of the water supply. For example, under conditions where freeze-up is highly probable, the hydraulics are quite unstable. Any further decrease in discharge results in increased pressure losses, such that the head requirements for flow are greater than the pump or other water source can supply. At this point flow ceases and freeze-up is immediate.

Gilpin noticed sporadic fluctuations in discharge and neck diameter near freeze-up that occurred rapidly and sometimes unexpectedly under conditions of flow that had existed for many hours. He also makes the important point that the pipe may freeze up during the transient phase of ice formation instead of during the steady-state phase. This could happen if the neck diameters were smaller than in the ultimate steady state, as was occasionally observed. The associated larger pressure losses and reduced flows would lead to rapid freeze-up. This situation would only occur if the cooling rate was high relative to the rate at which the steady-state ice-band structure developed. For buried pipe installations, this problem is remote because cooling rates are low. Similarly, the problem diminishes in importance for flows at higher Reynolds numbers, because the time required to reach steady state is shorter.

References

Gilpin, R.R. (1977a) The effects of dendritic ice formation in water pipes. *International Journal of Heat and Mass Transfer,* vol. 20, p. 693.

Gilpin, R.R. (1977b) A study of pipe freezing mechanisms. In *Utilities Delivery in Arctic Regions.* Environmental Protection Service, Environment Canada, Ottawa, Ontario, Report No. EPS 3-WP-77-1, p. 207-220.

Gilpin, R.R. (1977c) Ice formation in pipes. *Proceedings of the 2nd International Symposium on Cold Regions Engineering, 12-14 August 1976.* Cold Regions Engineers Professional Association, Fairbanks, Alaska, p. 4-11.

Gilpin, R.R. (1978) A study of factors affecting the ice nucleation temperature in a domestic water supply. *The Canadian Journal of Chemical Engineering,* vol. 56, p. 466-471.

Gilpin, R.R. (1979) The morphology of ice structure in a pipe at or near transition Reynolds numbers. *Heat Transfer*—San Diego, American Institute of Chemical Engineers Symposium Series, 189, vol. 75, p. 89-94.

Gilpin, R.R. (1981) Ice formation in a pipe containing flows in the transition and turbulent regimes. *ASME Journal of Heat Transfer,* vol. 103, p. 363-368.

McFadden, T. (1977) Freeze damage prevention in utility distribution lines. In *Utilities Delivery in Arctic Regions.* Environmental Protection Service, Environment Canada, Ottawa, Ontario, Report No. EPS 3-WP-77-1, p. 221-234.

Ozisik, M.N. and J.C. Mulligan (1969) Transient freezing of liquids in forced flow inside circular tubes. *ASME Journal of Heat Transfer*, vol. 91, p. 385–389.
Stephan, K. (1969) Influence of heat transfer on melting and solidification in forced flow. *International Journal of Heat and Mass Transfer*, vol. 12, p. 199–214.
Zerkle, R.D. and J.E. Sunderland (1968) The effect of liquid solidification in a tube upon laminar-flow heat transfer and pressure drop. *ASME Journal of Heat Transfer*, vol. 90, p. 183–190.

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